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Research article

Origin of the gas in the lower Miocene Barzalosa Formation, Upper Magdalena Valley Basin, Colombia

Origen del gas presente en la Formación Barzalosa, Mioceno inferior, Cuenca Valle Superior del Magdalena, Colombia

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ABSTRACT

The Upper Magdalena Basin is a prolific hydrocarbon-producing sedimentary basin in Colombia. Fluvial and lacustrine Mio-cene reservoirs within the basin comprise multiple horizons that, at first glance, appear to be isolated from one another. Gas accumulations have been identified deep in the stratigraphic column, particularly within the middle Miocene Barzalosa For-mation, whose source and connection to the regional petroleum system remain unknown. These reservoirs are embedded with-in fine-grained lacustrine and swamp deposits.

Molecular and isotopic analyses of the gases reveal a thermogenic origin for the hydrocarbons contained within these reser-voirs. The presence of thermogenic gas in the coarser-grained layers of the Barzalosa Formation implies a connection to a deeper basin source. The hydrocarbons likely migrated along adjacent fault systems, reaching the coarse-grained beds of the overlying La Victoria Formation (basal formation of the Honda Group), and subsequently moved through the unconformable contact that juxtaposes the permeable beds of Barzalosa and La Victoria formations. Keywords: Petroleum system, petroleum geology, thermogenic gas

RESUMEN

La Cuenca del Valle Superior del Magdalena es una región prolífica en la producción de hidrocarburos. Los yacimientos flu-viales y lacustres del Mioceno medio del área presentan múltiples horizontes que, a primera vista, parecen estar desconectados entre si. En particular, el origen del gas contenido en los yacimientos Mioceno medio correspondientes a la Formación Barza-losa y su relación con el sistema petrolífero regional ha sido, hasta ahora, poco comprendido. Estos yacimientos se encuentran embebidos en una matriz de depósitos lacustres y pantanosos.

No obstante, los análisis moleculares e isotópicos al gas almacenado en dichas capas permitieron establecer que su origen es termogénico, descartando así, una génesis biogénica. Este hallazgo sugiere una conexión directa con el sistema petrolífero re-gional y, a su vez, que la migración del gas probablemente ocurrió a través de las fallas de cabalgamiento adyacentes a la es-tructura hasta alcanzar las capas arenosas de la Formación La Victoria (unidad basal del Grupo Honda). Posteriormente, el gas habría continuado su migración a través del contacto discordante hasta alcanzar las capas más permeables que yacen en la parte superior de la Formación Barzalosa. Palabras clave: Geología del petróleo, sistema petrolífero, gas termogénico

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1. INTRODUCTION

The Upper Magdalena Basin (UMB) is an intramontane sedimentary basin that hosts significant conventional and unconventional hydrocarbon resources. It is bounded by the southern segments of the Central and Eastern Cordilleras of Colombia (Figures 1a and b). To date, approximately 631 million barrels of oil have been discovered in the basin (ANH, 2009), making it the third most prolific hydrocarbon-producing basin in Colombia (Sarmiento-Rojas and Rangel, 2004).

Historically, petroleum production in the UMB has been derived mainly from thick siliciclastic units within the Cretaceous and Cenozoic successions (Roncancio and Martínez, 2011). Wells within the study area (Figure 1c) have primarily targeted Middle Miocene fluvial-reservoirs of La Victoria Formation (Honda Group; Figure 2). However, several wells that drilled deeper intervals have encountered significant accumulations of methane hosted in thin and laterally discontinuous coarser-grained beds of the Barzalosa Formation (Figures 2, 4, and 5).

Methane is gas commonly generated by bacterial activity in wetland environments (Wuebbles and Hayhoe, 2000), and it is estimated that more than 70% of global natural methane emissions originate from wetlands (Khalil, 2000). Given that the Barzalosa Formation was deposited in lacustrine to swampy environment (De La Parra et al., 2009), it would be logical to consider this unit as a potential source of the observed gas. Moreover, numerous studies from different regions and geological ages—including Quaternary and Cenozoic rocks in Japan (Nakai, 1960), Cretaceous strata in Montana, United States (Rice, 1975), Cenozoic deposits in Russia (Alekseyev et al., 1973), and Quaternary sediments in China (Dang et al., 2008; TOC < 0.3%)—demonstrate that bacterial processes can generate commercial quantities of methane even in systems with relatively low organic content.

Alternatively, the gas encountered in the study area could be thermogenic in origin—generated from the thermal cracking of organic matter in deeper source rocks—implying a genetic connection to the regional Cretaceous petroleum system.

Because natural gas can originate from either biogenic or thermogenic processes (Fuex, 1997; Dembicki, 2017), accurately determining its origin is fundamental for basin modeling and resource assessment. In this context, identifying the gas source and migration pathways toward the reservoirs within the Barzalosa Formation is essential for developing a comprehensive understanding of the Miocene petroleum system of the UMB.

This study analyzes molecular and isotopic data from production gases of two Middle Miocene formations—the Barzalosa and La Victoria—to determine their origins and interactions, with particular emphasis on the final hydrocarbon migration pathway.

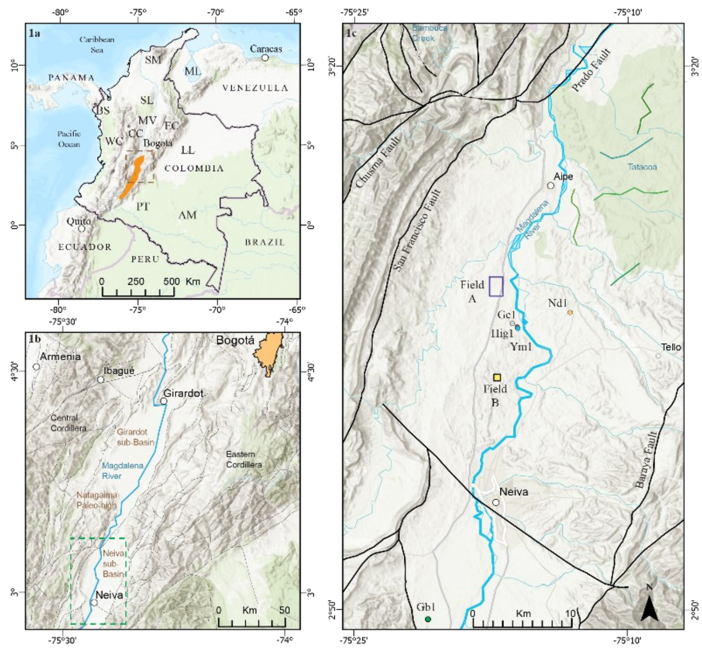

Figure 1. (a) Regional topographical map of the Andean Orogen showcasing major physiographic elements. Key geographic features are labeled, including the Santa Marta Massif (SM); San Lucas mountains (SL); Baudo mountains (BS); Western Cordillera (WC); Central Cordillera (CC); Eastern Cordillera (EC); Maracaibo Lake (ML); Llanos (LL); Putumayo (PT); Magdalena Valley (MV). The orange polygon delineates to Upper Magdalena Valley Basin (UMB). (b) Enlarged topographical map showing partially UMB's subdivisions (Girardot and Neiva sub-basins), with Bogota D.C., and Neiva as reference locations. (c) Detailed topographical map of a portion of the Neiva sub-basin, showing major surface faults (solid black lines). The purple square indicates the study area (Oil and Gas Field A) and its wells (W-1 through W-8), as well as the location of the structural map in Figure 3b. The yellow square marks the nearby Oil and Gas Field B and its reference well (W-9). For additional context, colored dots correspond to analyzed sites from De La Parra et al., (2019) within the UMB, and green lines denote geological transects from Anderson et al., (2016) across the Tatacoa Desert.

2. GEOLOGICAL BACKGROUND

2.1 Tectonic setting

The UMB is an intramontane basin situated between two branches of the northernmost Andes (Figure 1a). It is bounded to the west and east by the opposite verging Central and Eastern Cordilleras and their associated thrust systems, to the north by the Ibague Dextral Fault, and to the south by the junction of the Cordilleras (Mojica and Franco, 1990; Figure 1b). The basin is further subdivided into the Neiva and Girardot sub-basins (Figure 1b), separated by the Natagaima paleo-high (Mojica and Franco, 1990).

Extensional processes during the Early Cretaceous promoted continental, marginal-marine, and fully marine sedimentation across large portions of the northwestern margin of the South American continent (Mojica and Franco, 1990; Cooper et al., 1995; Sarmiento-Rojas, 2001). Since the Late Cretaceous, the region has experienced multiple orogenic episodes (Bayona et al., 2008; Horton, 2018; Calderon-Diaz et al., 2024).

The most significant of these are: the Eocene pre-Andean Orogeny, which peaked during the Middle Eocene (Villamil, 1999), and the Andean Orogeny, characterized by pulses of intense tectonic activity during the Middle Miocene and Pliocene-Pleistocene (Sarmiento-Rojas, 2001). This geodynamic evolution conditioned the sedimentary infill of the UMB, resulting in an overfilled retroarc foreland basin during the Cenozoic. Simultaneously, imposing complex combinations of thin and thick-skinned deformation structures throughout the basin (Mojica and Franco, 1990; Rosero et al., 2022).

2.2 Depositional setting

The upper sedimentary fill of the UMB comprises Cretaceous and Cenozoic strata. This study focuses on two Miocene units of the overfilled-Cenozoic succession preserved in the Neiva sub-basin: the Barzalosa Formation, and the La Victoria Formation of the Honda Group. Due to the series of orogenic events that took place in the region, several unconformities have influenced the stratigraphic relationships in the UMB. In the study area and around, the basal unit of the Cenozoic succession consists either of the coarse-grained beds of the Doima Formation, or the fine-grained beds of the Barzalosa Formation, both resting unconformably over older Cretaceous rocks.

In its type locality (northwest of Girardot), the Barzalosa Formation has been subdivided into three segments (De Porta, 1974, p. 84). The lower segment consists of thick conglomerates and gravels interbedded with minor mudstone layers; the middle segment is dominated by mudstones with frequent gypsum veins; and the upper segment comprises interbedded mudstones and ferruginous sandstone. The total thickness of the unit is approximately 300 meters. Although, core data are unavailable at the study site, well-log data reveal thin to very thin coarser-grained beds embedded within a fine-grained matrix (Figures 2, 4 and 5).

Based on the abundance of the algae *Pediastrum and Botryococcus*, the depositional environment of the Barzalosa Formation has been interpreted as lacustrine to swampy, that likely formed between ~17.5 and 16.5 Ma., (De La Parra et al., 2019; Figure 2). Such environments were not restricted to a local area, instead they extended northward into the Girardot sub-basin (e.g., Zapata et al., 2023) and further north into Middle Magdalena Basin; where the correlative deposits are known as the La Cira fossiliferous horizon (De La Parra et al., 2019). Coeval, marine and lacustrine conditions were also present in the Llanos and Amazon basins (e.g., Hoorn et al., 2010; Jaramillo et al., 2017).

The upper contact of the Barzalosa Formation is erosive, marking the arrival of higher-energy fluvial deposits of La Victoria Formation. The erosional event likely truncated portions of the upper Barzalosa deposits. The overlying Honda Group, based on a compilation of radiometric and paleomagnetic data (e.g., Flynn et al., 1997; Guerrero, 1997; Anderson et al., 2016; Mora-Rojas et al., 2023) was deposited between approximately 16 and 10.5 Ma (Mora-Rojas et al., 2023; Figure 2). However, the Honda Group may extend to slightly older ages, since the earliest date reported by Mora-Rojas et al., (2023) corresponds to a level 63 meters above the base of the La Victoria Formation. Therefore, the minor age difference between the Barzalosa (~16.5 Ma) and La Victoria (~16 Ma) formations suggests no significant depositional hiatus, other than the erosion associated with the arrival of the coarser-grained beds of the La Victoria Formation.

The Honda Group based on lithological differences observed in the outcropping areas, has been subdivided into the La Victoria Formation (lower) and the Villavieja Formation (upper) (Guerrero, 1997). Both formations represent fluvial deposits (Guerrero, 1997), although the La Victoria Formation contains a higher proportion of coarse-grained facies compared to the overlying Villavieja Formation (Villaroel et al., 1996). The coarse-grained rocks have been classified as volcanic litho-arenites, whereas the fine-grained rocks consist of greenish-gay and reddish-brown mudstones (Gerrero, 1997).

The contact between the La Victoria and Villavieja formations is conformable and can be estimated to be slightly younger than ~12.58-11.41 Ma (Takemura and Danhara, 1985; Figure 2). The succession is ultimately capped by a disconformity which separates the Villavieja Formation from the coarser-grained strata of the Gigante Formation (Guerrero, 1997; Figure 2). Although, the Gigante Formation has been reported in nearby areas (Guerrero, 1997), surface geological maps indicate that the Honda Group is the primary unit exposed at the study site (c.f. Marquínez and Velandia, 2001; Figures 2 and 3a).

It is worth mentioning that the mud-to-sand ratio inferred from the stratigraphic columns of the Honda Group north or the study area (i.e., Flynn et al., 1997, Guerrero, 1997; Anderson et al., 2016; Mora-Rojas et al., 2023) is significantly higher than the one inferred from the gamma-ray logs in Figures 2 and 3. In fact, the study area exhibits a clear dominance of coarse-grained lithologies, such as sandstones and conglomerates, over mudrocks. This discrepancy likely reflects the changing nature of the fluvial environments, where some areas are dominated by overbank deposits, while others are characterized by channelized systems.

2.3 Subsurface structure

The study area (hydrocarbon Field A) is located approximately 210 km southwest of Bogota D.C., (Figures 1b, 3a, and 3b). This field targets the Neogene succession, which has been shaped into an elongated antiform striking 25°NE (Figure 3b), aligned with the major fault systems in the region, such as the San Francisco and Chusma faults (Figure 3a).

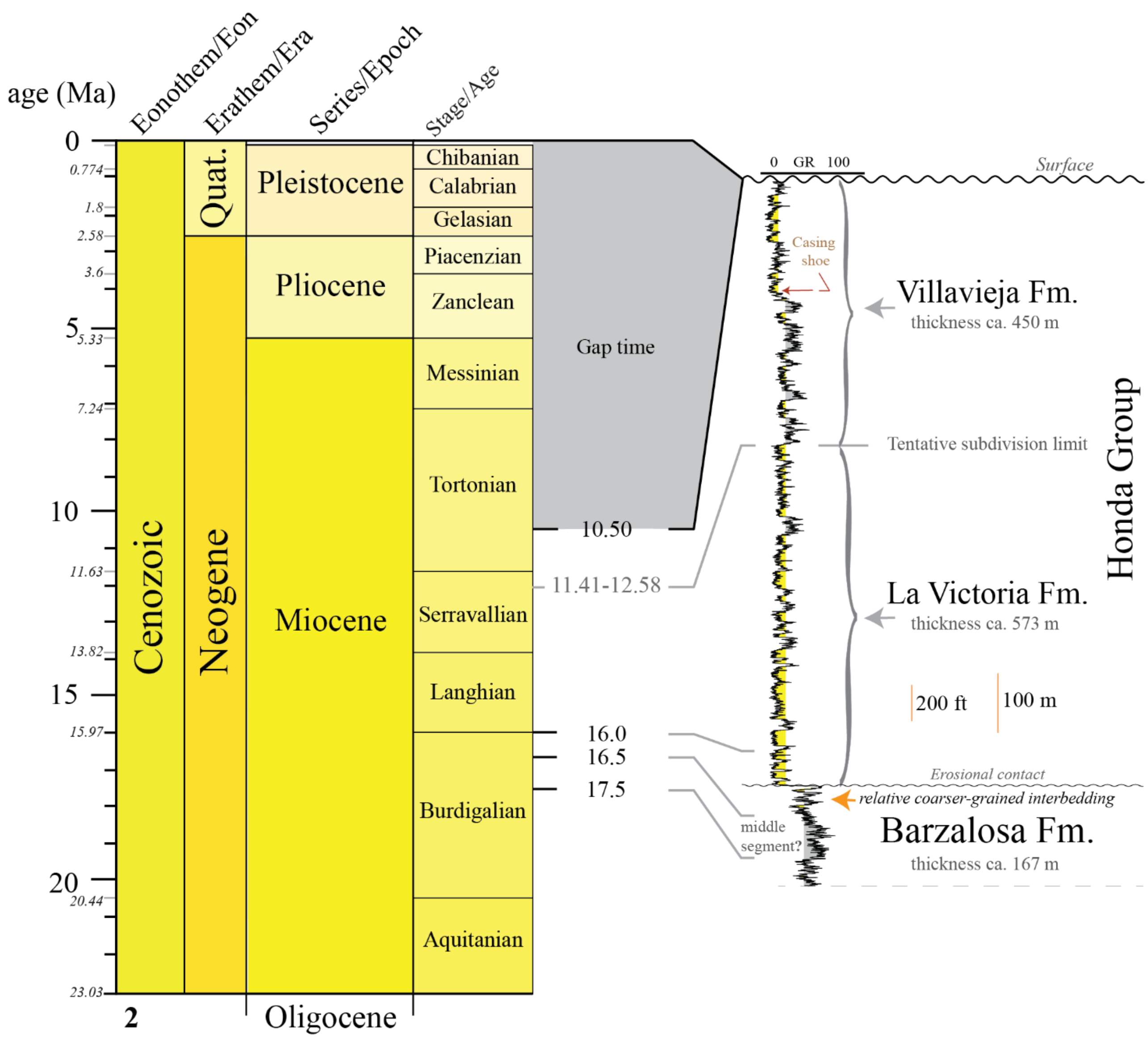

Figure 2. Local chronostratigraphic chart of Miocene units in the Neiva sub-basin (Upper Magdalena Valley Basin). The Gamma ray log is derived from several representative locations within and near the study area. Temporal constraints for the Honda Group are based on the compilation by Mora-Rojas et al., (2023), whereas the Barzalosa Formation timeline follows the preliminary estimations of De La Parra et al. (2019). It should be noted that De La Parra et al., (2019) indicated the ages of the Barzalosa Formation may extend beyond the 16.5 and 17.5 Ma range, as those values represent solely the middle segment of the formation. The precise subdivision of the Barzalosa intervals remains uncertain due to the lack of direct age calibration or biostratigraphic control. Surface geological map (i.e., Marquínez and Velandia, 2001) indicate that the upper part of the Honda Group is this area.

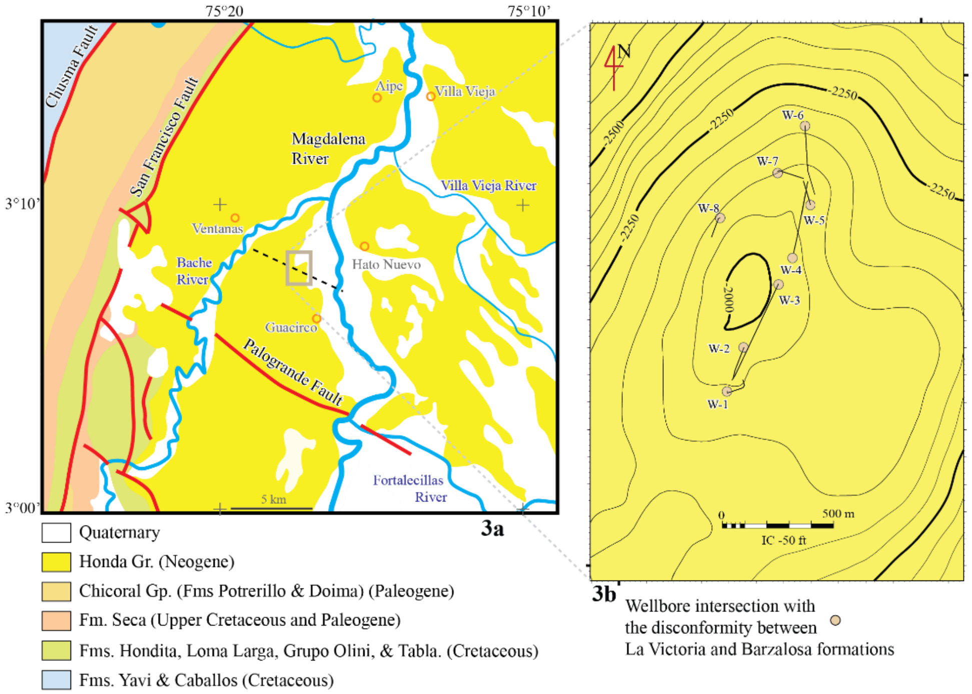

Figure 3. . (a)) Surface geological map modified from Marquinez and Velandia, (2001). The map highlights major structural and stratigraphic elements, including key fault systems. The dashed line indicates the location of the seismic pro-file shown in Figure 11c. (b) True vertical depth subsea (TVDss in feet) structural map of the disconformity sur-face between the Barzalosa and La Victoria formations at Field A. The trap geometry is inferred to have formed after the deposition of the Honda Group (late Miocene; Fig. 2), as the Honda strata exhibit similar structural trends and geometries. Alternatively, it could represent the final pulse associated with the Andean Orogeny during the Pliocene-Pleistocene interval (Figure 2), as suggested by regional studies (e.g., Villamil, 1999; Sarmiento-Rojas, 2001). Notable parallelism is observed between the subsurface structure and major fault systems such as the San Francisco and Chusma faults.

2.4 Reservoirs

Gas reservoirs within the La Victoria Formation are situated immediately above the erosive contact that separates it from the Barzalosa Formation (Figure 4). Two oil-producing intervals lie above the gas-bearing zone, and a third oil interval is located farther up-section, separated by water-bearing layers. Similarly, gas reservoirs in the Barzalosa Formation are positioned below the disconformity, but are hosted in thinner and more discontin-ues beds compared to those of the La Victoria Formation (Fig-ure 4).

2.5 Drilling mud gases

Drilling mud gas is routinely analyzed to identify potential hydrocarbon accumulations. For instance, a complete chroma-tography (C_1–C_5) typically indicates the presence of oil or con-densate accumulations, whereas an incomplete chromatography may reflect either dry gas or water-bearing zones. In Field A, the concentrations of n- and i- pentane (C_5), and methane (C_1) gases show a direct correlation with the type of hydrocarbon produced from each interval. In this case, the elevated C_5 con-centrations are associated liquid hydrocarbons, whereas higher C_1 levels correspond to gas accumulations (Figure 5).

This relationship is further supported by core data from wells W-1 and W-7 in Field A. In the lower cored interval of W-1 (approximately 130 ft; Figure 4), only a 2-ft section exhib-ited oil staining, whereas the remaining 128 ft were unstained, matching very well the gas production from those intervals and the mud-gas chromatography. Conversely, in the upper cored intervals of W-1 and W-7, the coarser-grained packages were oil-stained, corresponding to oil-production zones and in agree-ment with the mud-gas chromatography data.

3. METHOD

To determine the origin of the hydrocarbons in Field A, mo-lecular and isotopic analyses were conducted. A total of nine samples were collected—eight from Field A and one from Field B (Figure 1). Samples from Field A are distributed as follows: wells W-2 and W-4 produce exclusively from the Barzalosa Formation, whereas wells W-3 and W-8 produce solely from the La Victoria Formation. The remaining wells (W-5, W-6 and W-7) produce from both formations (Figure. 4). Sample from Field B serves as a reference for comparison. To ensure analyt-ical precision, two replicate samples were obtained from W-3 (Tables 1, 2, and 3). All isotopic and compositional analyses were conducted by Isotech.

Gas composition was analyzed using a Shimadzu 2010 gas chromatograph, while carbon and hydrogen iso-topic ratios were measured using a Finnigan MAT Delta S mass spectrom-eter. Chemical compositions were normalized to 100%. The hy-drogen isotopic composition is reported relative to VSMOW, and the carbon isotopic composition relative to VPDB. Carbon isotope values for all gas components were calibrated using a two-point scale based on LSVEC and NBS-19 standards.

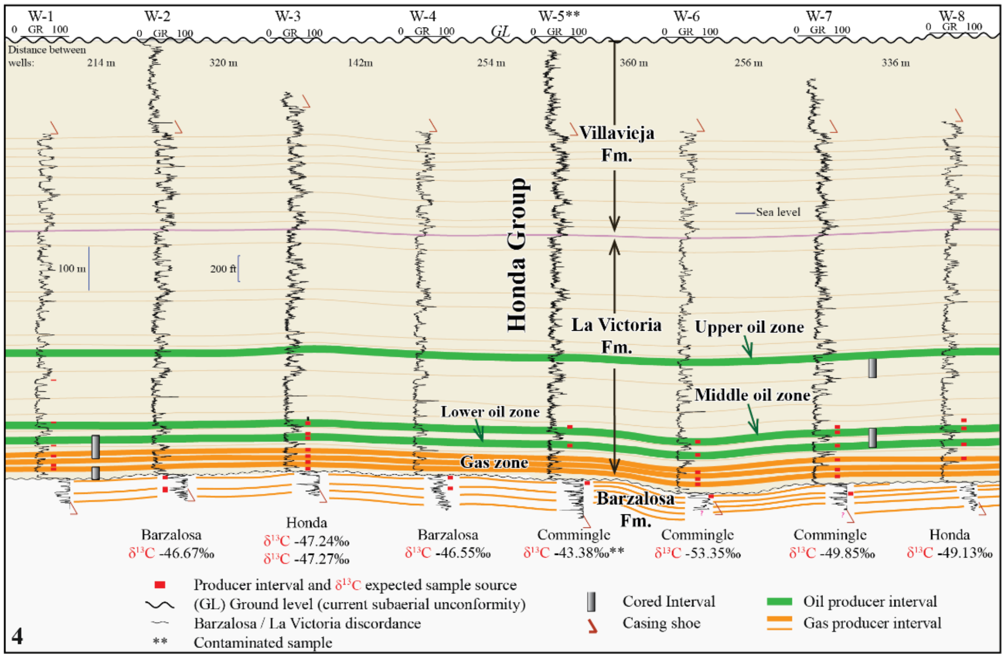

Figure 4. Structural and lithostratigraphic well cross-section of Field A showing reservoir zones and lithostratigraphic units. Wells W-2 and W-4 produce exclusively from the Barzalosa Formation, whereas wells W-3 and W-8 produce solely from the La Victoria Formation. Wells (W-5, 6 and 7) have commingled production from both formations. The intervals analyzed for isotopic and compositional data are marked as small red segments within the reservoirs. The sample from W-5 was classified as contaminated. Well locations correspond to those shown in Figure 3b. Some wells lack the upper portion of the gamma ray log (i.e., W-1, W-3, W-4, W-6, W-7, and W-8). The ground surface is indicated by the wavy line at the top of the plot. The horizontal well distance was measured at the disconformity between the La Victoria and Barzalosa formations.

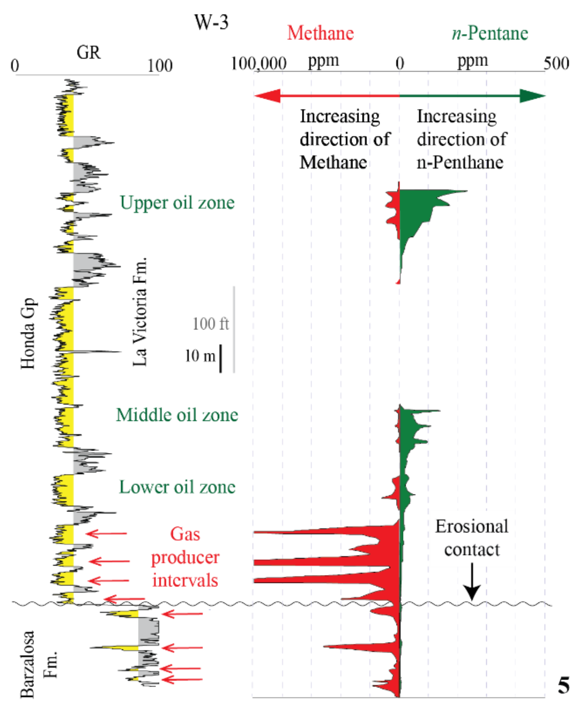

Figure 5. Methane (C_1) and n-Pentane (n-C_5) mudlogging gas profiles from well W-3. Methane and n-Pentane plots are displayed in opposite directions to emphasize the relative dominance of gas or oil, marking the zones of hydrocarbon-bearing zones by type. Methane mud-gas shows occur both above and below the discordance between the Barzalosa and La Victoria formations, indicating the presence of hydrocarbons across the contact.

Table 1. Non-hydrocarbon composition for wells from Field A and W-9 from Field B; * indicates a repeated sample; ** indicates a contaminated sample; nd = not detected.

Sample (Well)	Formation	GC Date	He %	H_2 %	Ar %	O_2 %	CO_2 %	N_2 %	CO %
W-2	Barzalosa	11/30/2018	0.0232	nd	0.0167	nd	0.013	2.46	nd
W-3	La Victoria	11/30/2018	0.0139	nd	0.0172	nd	0.007	1.64	nd
W-3*	La Victoria	12/3/2018	0.0131	nd	0.018	nd	0.006	1.65	nd
W-4	Barzalosa	11/30/2018	0.0233	nd	0.0156	nd	0.012	2.31	nd
W-5**	Commingled	11/30/2018	0.0068	nd	0.412	9.41	0.14	34.41	nd
W-6	Commingled	11/30/2018	0.0121	0.0642	0.0444	0.014	0.028	3.91	nd
W-7	Commingled	11/30/2018	0.0053	nd	0.0259	0.012	0.007	1.53	nd
W-8	La Victoria	11/30/2018	0.0095	nd	0.0316	nd	0.086	2.36	nd
W-9	La Victoria	11/30/2018	0.0095	nd	0.0182	nd	0.028	2.83	nd

Table 2. Hydrocarbon composition from wells of Field A and W-9 from Field B; * indicates a repeated sample; ** indicates a contaminated sample; nd = not detected

Sample (Well)	C_1 %	C_2 %	C_2H_4 %	C_3 %	C_3H_6 %	iC_4 %	nC_4 %	iC_5 %	nC_5 %	C_6+ %
W-2	93.41	1.7	0.0002	1.48	0.0002	0.14	0.37	0.0819	0.0637	0.24
W-3	92.83	1.74	nd	1.51	nd	0.63	0.707	0.375	0.195	0.33
W-3*	92.79	1.73	nd	1.51	nd	0.632	0.711	0.38	0.198	0.36
W-4	93.76	1.63	0.0001	1.4	0.0002	0.125	0.33	0.0709	0.0572	0.261
W-5**	52.87	0.392	nd	0.431	nd	0.333	0.429	0.405	0.242	0.519
W-6	84.07	1.6	nd	2.16	nd	2.88	1.51	1.88	0.508	1.32
W-7	70.69	4.72	nd	8.43	nd	3.53	5.57	2.42	1.43	1.63
W-8	90.44	2.55	nd	2.23	nd	0.667	0.854	0.323	0.194	0.251
W-9	78.3	7.95	nd	6.63	nd	0.983	1.96	0.49	0.379	0.423

Table 3. Isotopic composition for wells from Field A and W-9 from Field B; * indicates a repeated sample; ** indicates a contaminated sample; nd = not detected

Sample (Well)	Sample Date	Molecular Date	$\delta^{13}C_1$ ‰	$\delta^{13}C_2$ ‰	$\delta^{13}C_3$ ‰	δDC_1 ‰	Specific Gravity	BTU
W-2	11/3/2018	12/4/2018	-46.67	-33.73	-26.25	-196.1	0.603	1049
W-3	11/3/2018	12/4/2018	-47.24	-29.82	-29.15	-208.6	0.622	1093
W-3*	11/3/2018	12/6/2018	-47.27	-29.79	-29.09	-205.3	0.623	1095
W-4	11/4/2018	12/6/2018	-46.55	-33.81	-26.01	-200.1	0.6	1048
W-5**	11/3/2018	12/4/2018	-43.38	-27.88	-28.7	-200.3	0.795	629
W-6	11/4/2018	12/6/2018	-53.35	-27.76	-29.31	-220.6	0.741	1240
W-7	11/4/2018	12/6/2018	-49.85	-31.27	-29.83	-210.6	0.911	1550
W-8	11/3/2018	12/4/2018	-49.13	-30.29	-29.23	-218.5	0.637	1102
W-9	11/3/2018	12/4/2018	-49.28	-33.83	-31.85	-229	0.739	1256

4. RESULTS

The sample from well W-5 exhibits relatively high concentrations of oxygen and nitrogen, suggesting contamination from surface or shallow sources (Figure 6; Table 1). In contrast, the remaining samples are characterized by high hydrocarbon concentrations and low levels of non-hydrocarbon molecules (Figure 7; Table 2).

Within the subordinate non-hydrocarbon fraction, only nitrogen (N_2) exceeds 1%, with concentrations ranging from 1.53% to 3.91%. Other molecules, including helium (He), hydrogen (H_2), argon (Ar), oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO), occur only in trace amounts, each below 0.1% (Figure 7). The hydrocarbon fraction is overwhelmingly dominated by methane (C_1), whose concentrations vary between 70.69% and 93.76% across the analyzed samples. Notably, higher methane percentages are observed in the Barzalosa Formation (wells 2 and 4) a fact that a first glance could suggest a possible biogenic gas origin.

In general, hydrocarbon abundances decrease systematically with increasing chain length ($C_1 > C_2 > C_3 > C_4 > C_5 > C_6$). However, samples from wells W-6 and W-7 show minor deviations from this trend. In W-7, propane (C_3) exceeds ethane (C_2), ($C_3 > C_2$), while in W-6, both butane (C_4) and propane (C_3) are more abundant than ethane (C_2), ($C_4 > C_3 > C_2$), (Figures 7 and 8).

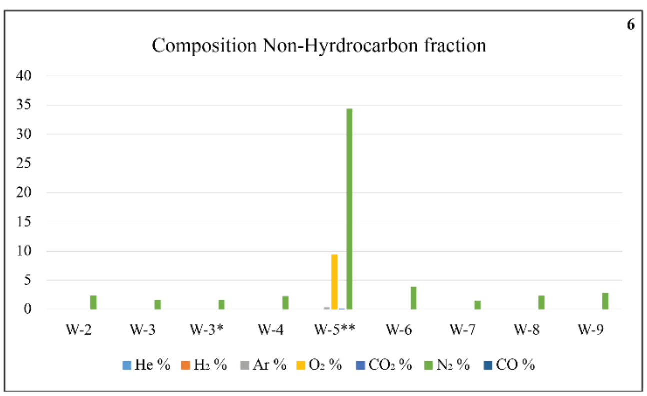

Figure 6. Non-hydrocarbon fraction composition across sampled wells. The exceptionally high concentrations of oxygen (O_2) and nitrogen (N_2) in well W-5 confirm contamination in this sample.

Regarding the stable carbon isotope composition ($\delta^{13}C$), most samples follow the expected progressive enrichment trend ($\delta^{13}C_1 < \delta^{13}C_2 < \delta^{13}C_3$), which rules out secondary thermal processes as a major control on gas composition. However, in well W-6, an isotopic reversal is observed between ethane and propane ($\delta^{13}C_2 > \delta^{13}C_3$), sug-gesting a mixture of biogenic and thermogenic gases (Table 3; Figure 10). For hydrogen isotopes, only δD_1 could be measured, with values ranging from –229‰ to –196.1‰.

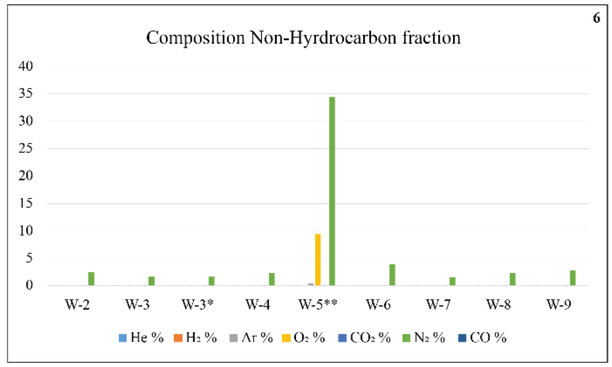

Figure 7. Non-hydrocarbon fraction composition (excluding contaminated sample well W-5). Nitrogen (N_2) is the dominant non-hydrocarbon component across all samples, while other gases such as helium (He), hydrogen (H_2), argon (Ar), oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO) occur only in trace amounts.

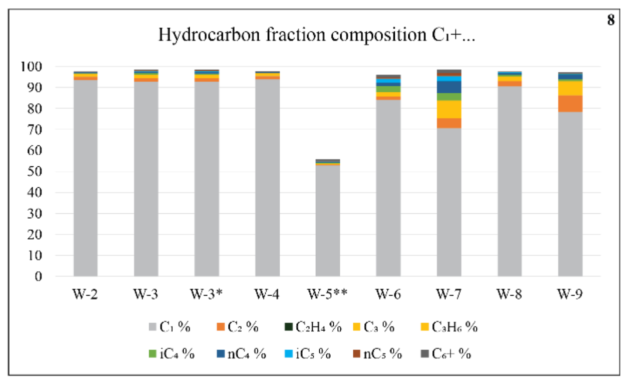

Figure 8. Hydrocarbon fraction composition (C_1+...). Methane (C_1) dominates the hydrocarbon group across all samples.

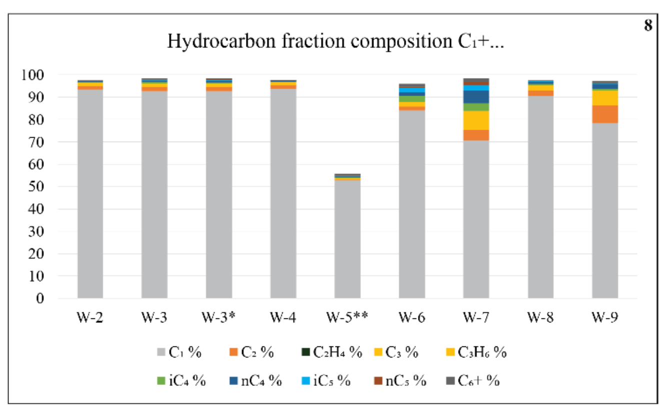

Figure 9. Hydrocarbon fraction composition (C_2+...).

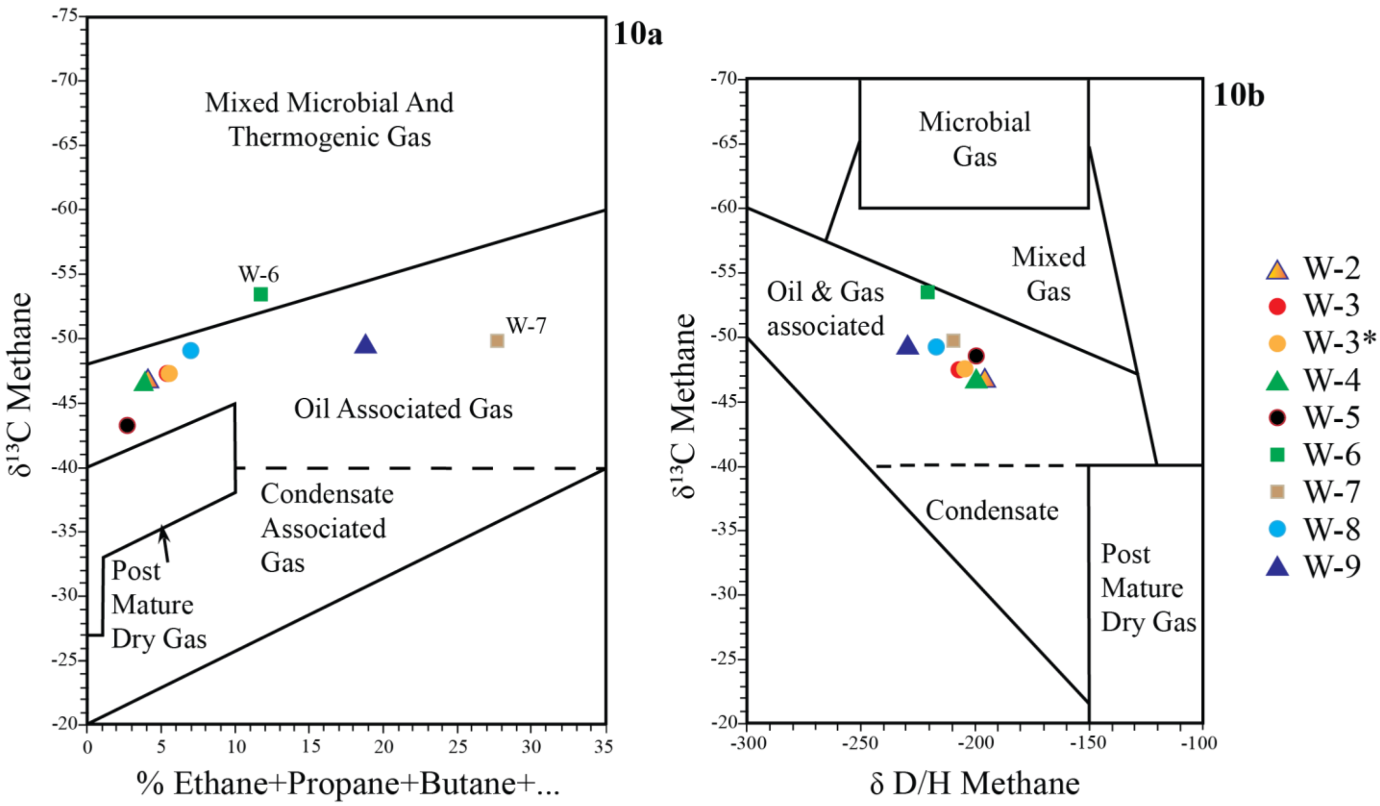

Figure 10 Isotopic and Molecular cross plot for this study (a) $\delta^{13}C_1$ methane vs. cumulative concentrations of ethane, propane, butanes, pentanes, and hexanes (C_2^+). (b) δ13C_1 vs δD/H (methane). Base diagrams adapted from Schoell, (1983). Repeated/control sample (*).

5. DISCUSSION

Molecular composition is one of the main tools for identifying the origin of hydrocarbons. Hydrocarbon fractions with C_2+… concentrations above 1–2% are generally indicative of thermogenic processes (Fuex, 1997). That said, W-2 and W-4, despite having the lowest C_2+… concentrations among all analyzed sites (4.08% and 3.87%, respectively; Table 2), still suggest a thermogenic origin for the gas within the Barzalosa Formation.

Higher C_2+… concentrations were observed in the remaining sites, further supporting a thermogenic origin (e.g., Schoell, 1979), although, these higher values of C_2+… (ranging from 5.49 to 27.73% in W-3, W-6, W-7, and W-8; Table 2; Figure 4) correspond to commingled production of oil and gas intervals mainly from La Victoria Formation but also from the Barzalosa Formation (W-6, W-7; Table 2; Figure 4).

As with molecular composition, stable isotope concentrations are valuable in determining the origin of hydro-carbons. Isotopic data from Field A indicate that gas samples from the Barzalosa Formation (W-2 and W-4; Figures 4, 10a, and 10b) are thermogenic in origin.

As previously stated, our integrated data thus suggest that the gas hosted within the coarser-grained beds of Barzalosa Formation, immediately below the erosive contact with the La Victoria Formation (Figures 2, 4, 5, 11b, and 11c), is of thermal origin. However, the absence of biogenic gas in the sandier intervals of the Barzalosa Formation—deposits expected to host some biogenic gas given their lacustrine to swampy depositional setting—requires explanation. We propose that biogenic gas initially generated in the Barzalosa Formation and still stored in its coarser-grained beds, escaped during the early stages of La Victoria deposition. The onset of fluvial sedimentation of the La Victoria Formation likely caused erosion and removal of the uppermost Barzalosa beds, placing the coarse-grained deposits of both units in unconformable contact. This erosional reworking and hydraulic connectivity may have facilitated gas leakage, which could have continued throughout the deposition of the La Victoria Formation (Figure 11a).

Furthermore, our data indicate that the unconformable contact between the La Victoria and Barzalosa formations is permeable. The presence of thermogenic gas within the thin and discontinuous coarse-grained beds of the Barzalosa Formation supports this interpretation, as this unit did not attain the thermal maturity required to generate hydrocarbons independently. In this scenario, the final migration pathway likely followed the coarse-grained beds of the La Victoria Formation (Lower Honda Group), and wherever the coarse-grained beds of the La Victoria and Barzalosa were juxtaposed, the migration front appears to have extended into the Barzalosa For-mation (Figures 11b, and 11c).

Most samples from the La Victoria Formation are also classified as thermogenic, with the exception of well W-6. whose isotopic and molecular signatures (Figure 10a) suggest a mixed origin. However, when hydrogen iso-topes ratios (δD/H) are considered (Figure 10b), the gas from W-6 is still classified as thermogenic, though near the mixed-origin boundary. It is worth noting that the classification boundaries in Figures 10a and 10b carry a degree of uncertainty, given the complexity of processes influencing isotopic fractionation (Liu et al., 2019). An alternative explanation in line with previous hypothesis, is that some escaped biogenic gas volumes from the Barzalosa Formation could have been trapped within the early sedimentation beds of the La Victoria Formation, and subsequently mixing with thermogenic gases.

The possibility of biogenic gas from the La Victoria Formation also remains plausible. The depositional setting of this unit—a meandering fluvial belt, interspersed with swamp and lacustrine environments at least for some intervals—supports this possibility. Evidence includes black mudstones beds, and an abundant fossil record, including crocodiles, fish, turtles, and bivalves, (see Guerrero, 1997, p. 35). Similarly, the palynological data showing significant counts of Botryococcus algae in nearby wells (see De La Parra et al., 2019, p. 499, wells GC-1 Hig-1; Figure 1c), reflect aquatic organic productivity and preservation within the La Victoria Formation (Lower Honda Group).

As previously discussed, molecular and isotopic analyses of exclusive samples from the Barzalosa Formation (i.e., W-2 and W-4; Figure 4; Table 2) rule out the occurrence of biogenic gas from this formation, at least for the study area, however, for the La Victoria Formation, one sample may be classified as having a mixed origin. If this is the case, a new question emerges: is this biogenic gas the result from primary bacterial activity during the sedimentation or from secondary activity (hydrocarbon biodegradation)?

To distinguish between these processes, it is necessary to consider the geological conditions required for bacterial gas generation associated. This includes an assessment of the minor black mudstones interpreted as swampy/lacustrine deposits and the processes involved in hydrocarbon biodegradation within the reservoirs.

Although total organic carbon (TOC) and vitrinite reflectance data for the La Victoria or Barzalosa formations at the study site are unavailable, the depositional environments of certain intervals within the La Victoria Formation (lacustrine and swamp) and much of the Barzalosa Formation, are clearly favorable for the accumulation of organic matter under conditions suitable for bacterial activity and microbial gas generation.

In the case of secondary activity, the thermal history of the stratigraphic sequence is crucial, as bacterial processes are restricted to low-temperature conditions (below 80°C). Bottom-hole temperature measurements from Field A indicate a thermal gradient of approximately 23.6°C/km, corresponding to a present-day temperature range of 36–44°C in the target units. A straightforward approach to estimate the maximum thermal history of the Barzalosa Formation involves considering the eroded overburden section of the Honda Group, calculated from the structural relief of this field (and knowing that deformation timing of this structural trap was later than deposition of the Honda Group), it is evident that the maximum temperature experienced by both the Barzalosa Formation and Honda Group remained below 80°C. This indicates that the entire stratigraphic section of interest has been within the temperature range suitable for bacterial activity since deposition. temperature range suitable for bacterial activity since deposition. Moreover, since thermogenic oil generation and expulsion from the Cretaceous source rocks postdate the Honda Group deposition (Sarmiento-Rojas, 2001), hydrocarbons in Field A have remained within the bacterial degradation threshold.

Therefore, the geologic conditions and thermal history satisfy the conditions for biogenic gas production either primary and/or secondary activity in Field A.

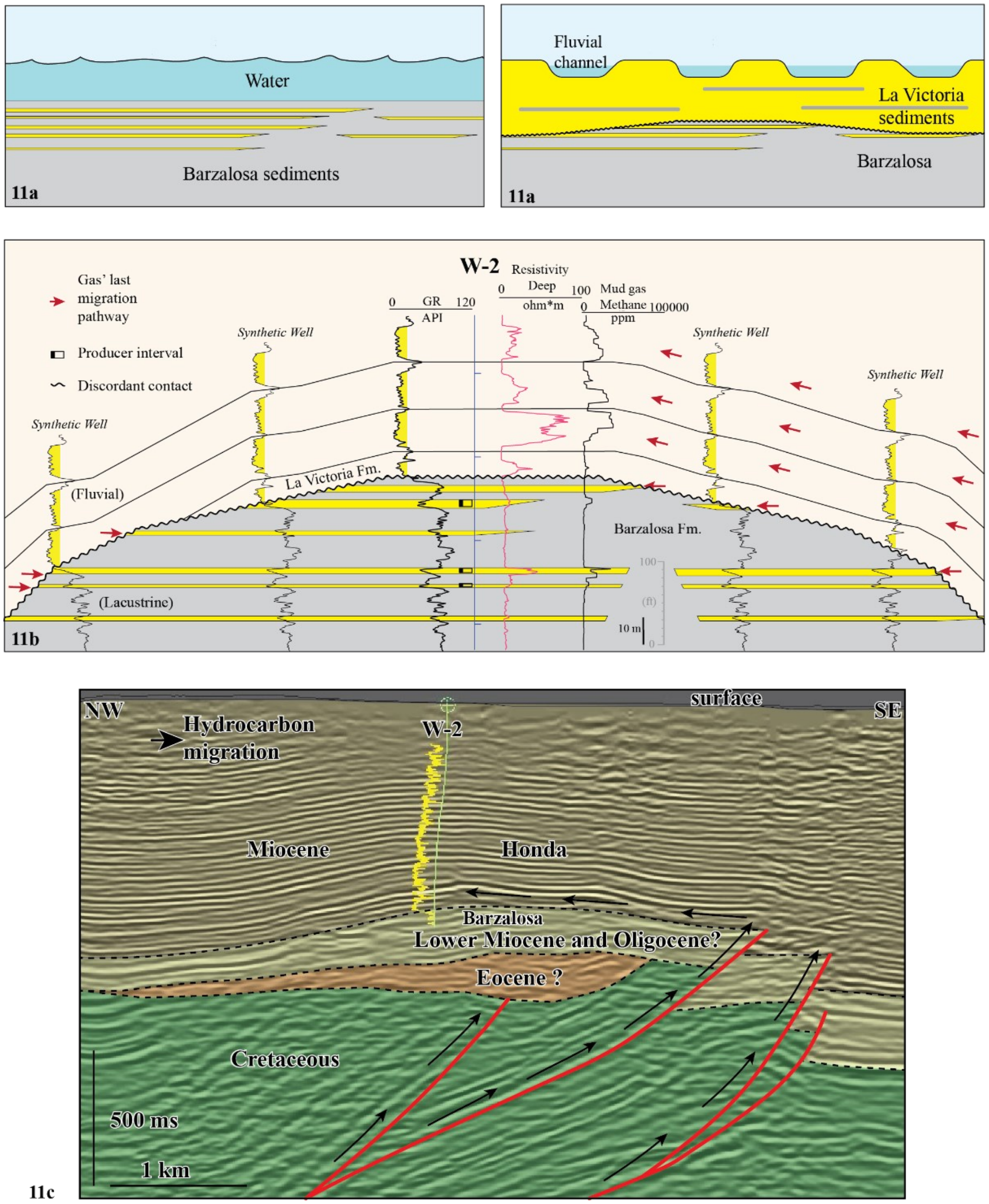

Figure 11. Interpretative model illustrating the depositional environment of the Barzalosa Formation, the erosion of its uppermost beds, the subsequent sedimentation of the La Victoria Formation, and the migration and charge pathways affecting the upper coarse-grained beds of the Barzalosa and La Victoria formations.

(a) Interbedding of coarse- and fine-grained beds in the Barzalosa Formation; the coarse-grained beds may have initially stored biogenic gas generated by bacterial activity. Subsequently, the arrival of the fluvial deposits of the La Victoria Formation eroded part of the uppermost Barzalosa sediments. The previously accumulated biogenic gas likely leaked upward into the coarse-grained beds of the La Victoria Formation and eventually escaped to the surface.

(b) The irregular surface of the unconformity juxtaposes permeable beds of the La Victoria and Barzalosa formations, facilitating gas migration and subsequent hydrocarbon charge in the thin but coarser-grained beds of the middle member of the Barzalosa Formation. Despite their limited thickness and poor development, well W-2 has produced over 505 million cubic feet of gas (equivalent to approximately 89,964 barrels of oil) since the onset of production in 2016 and is still producing at the time of submission of this paper (April 2025). The resistivity log is displayed in linear scale to optimize the visualization and identification of pay zones within the reservoir.

(c) Interpreted seismic line oriented perpendicular to the regional tectonic regime that originated the structure. The section location is shown in Figure 3a. Hydrocarbon migration most likely occurred along the frontal fault systems, subsequently reaching the La Victoria Formation beds and moving laterally toward higher structural positions (i.e., zones of lower pressure).

6. CONCLUSIONS

Isotopic and compositional concentrations indicate that the gas stored within the thin beds of the Barzalosa Formation originated from thermal rather than biogenic processes. Similarly, geochemical data from hydrocarbons in the La Victoria Formation (Lower Honda), point to a predominantly thermogenic origin. However, one sample from well W-6, representing a commingled production interval, suggests a potential mixture with biogenic gas, possibly derived from either primary bacterial activity or secondary hydrocarbon biodegradation.

The close similarity between the isotopic signatures of the gases from both formations suggests that the Barzalosa reservoirs are genetically linked to the same regional petroleum systems as the La Victoria Formation. We propose that a hydrocarbon fluid pulse generated in the deeper parts of the basin migrated upward (most likely along a fault system; Figure 11c) into the coarse-grained beds of the La Victoria Formation, subsequently moved through the unconformable contact between the La Victoria and Barzalosa formations. The last migration pathway likely occurred where permeable beds from both formations are juxtaposed across the disconformity, enabling fluid flow and eventual trapping within the Barzalosa Formation (Figure 11b).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to the publication of this paper.

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